Design Considerations for Heavily-Doped Cryogenic Schottky Diode Varactor Multipliers

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Current state-of-the art solid-state sources above 500 GHz are constructed from chains of cascaded Schottky-barrier varactor diode frequency multipliers. To achieve the performance required for these multipliers above 200 GHz requires varactor diodes using doping concentrations above 1×10^{17} cm^{-3}. At these high doping levels, effects neglected in device analyses commonly used in design become important. These include degeneracy in the bulk semiconductor and quantum mechanical tunneling through the barrier. Degeneracy reduces the conductivity and makes it much more temperature dependent than lower doped diodes. For instance, a diode with an equilibrium carrier concentration n_0 of 5×10^{17} cm^{-3} has an approximate donor concentration of 3×10^{18} cm^{-3} and a carrier concentration of only 1.7×10^{17} cm^{-3} at a temperature of 100 K. Since the depletion region in such highly doped diodes is narrow, current flow is dominated by tunneling through the Schottky barrier, resulting in a "leaky" diode with no real reverse saturation and a high ideality factor. Tunneling currents have been calculated using the transfer matrix method [1], and simple formulae fit to them for inclusion in a harmonic balance non-linear simulator. For the above-mentioned diode, the ideality factor is 1.7 at 300 K but around 5 at 100 K. In the reverse direction, the magnitude of the reverse current at –2 volts is as high as at 0.5 Volts forward: 1.5×10^6 A/m^2 corresponding to 1.5 μA for a 1 μm × 1 μm anode diode. This is many orders of magnitude higher than predicted by the thermionic emission theory. Temperature-dependent breakdown calculations have also been made using ionization rates derived using the Okuto-Crowell model [2].

Test diodes have been fabricated at JPL, and detailed I/V measurements made on them down to 80 K in a cryostat. Comparisons between these measurements and the I/V calculations will be presented. Additionally, because of carrier velocity saturation at high frequencies and powers [3], electrons at the edge of the diode depletion region cannot follow the electric field, resulting in lower capacitance modulation than the quasi-static models assume. The efficiency degradation due to these factors will be analyzed for their effect on design of multipliers for high frequency, low temperature operation.

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[1] Y. Ando and T. Itoh, "Calculation of Transmission Tunneling Current Across Arbitrary Potential Barriers," J. Appl. Phys., Vol. 61, no. 4, pp. 1497-1502, Feb. 1987.

[2] Y. Okuto and C.R. Crowell, "Energy-Conservation Considerations in the Characterization of Impact Ionization in Semiconductors," Phys. Rev. B, Vol. 6, no. 8, pp. 3076-3081, 15 Oct. 1972.

[3] E. L. Kollberg, T. J. Tolmunen, M. A. Frerking and J. R. East, "Current Saturation in Submillimeter Wave Varactors," IEEE Trans. Microwave Theory Techniques, Vol. 40, no. 5, pp. 831-838, May 1992.